AATCC Review

23 October 2024: Received
18 January 2025: Revised
13 February 2025: Accepted
16 February 2025: Available Online

https://aatcc.peerjournals.net/

Review Article | Open Access

NanoLeap: Exploring the Frontiers of Nanotechnology

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ABSTRACT

Agriculture, historically pivotal and stable, faces pressing challenges amidst global population growth and dwindling natural resources. To meet these challenges sustainably, agriculture must integrate social inclusion, health, climate resilience, and environmental stewardship into cohesive strategies. Nanotechnology plays a crucial role here, with applications such as nanofertilizers, nanopesticides, and nanosensors optimizing nutrient delivery, enhancing pest control, and monitoring soil health. These advancements promise to mitigate the adverse impacts of conventional agricultural practices, ensuring food security while promoting environmental conservation. Nanotechnology is rapidly emerging as a crucial tool in modern agriculture, poised to become a significant economic driver. This science manipulates materials at the nano-scale, revolutionizing agricultural production, processing, storage, packaging, and transportation. By employing novel chemical agents and delivery systems, nanotechnology enhances crop productivity while reducing reliance on bulk agrochemicals, thus facilitating precision farming and addressing challenges like weed management and environmental contamination. Nano-herbicides and metal nanoparticles offer innovative solutions to persistent agricultural issues, demonstrating promising results in improving crop yields and sustainability. In India, the widespread use of pesticides, weedicides and fertilizers has raised environmental and health concerns, prompting the development of nanopesticides, nano-herbicides, and nano-fertilizers. These nano-sized formulations offer improved efficacy and reduced environmental impact compared to conventional fertilizers, herbicides, and pesticides, though concerns persist about their long-term effects post-application. Despite its potential, the adoption of nanotechnology in agriculture faces challenges, including concerns over nanoparticle toxicity and regulatory frameworks. Additionally, the high cost of nanomaterials, limited farmer awareness, and the need for specialized infrastructure pose significant barriers to widespread implementation. Research efforts focus on understanding nanoparticle interactions with plants at molecular levels, aiming to unlock their full potential in enhancing crop resilience and productivity. However, further advancements are needed to bridge the gap between laboratory research and practical field applications, ensuring responsible and effective deployment of nanotechnologies in agriculture.

Keywords: *climate resilience; nanotechnology; nanoherbicides; nanofertilizers; nanopesticides; nanosensors; sustainable agriculture*

Introduction

Nanotechnology operates at the nanoscale, manipulating matter to design, characterize, fabricate, and apply structures and systems with precise control over their shape and size (11). Positioned as a transformative tool in modern agriculture, nanotechnology promises significant economic growth potential by enhancing crop productivity and reducing reliance on conventional agrochemicals. This innovation is crucial for addressing pressing challenges in agriculture, which supports over 60% of populations in many developing nations, particularly in weed management where conventional methods fall short (51). Despite its promise, there's a notable global scarcity of scientific research on practical applications of nanotechnology in agriculture. Nevertheless, its direct applications span agrochemicals, nanoscale carriers, smart packaging, and nanosensors, and extend into veterinary medicine, fisheries, and aquaculture. As a cornerstone of food and feed industries, agriculture faces mounting pressures such as population growth, shrinking arable land, water scarcity, soil degradation, and climate change, necessitating advanced technologies like nanotechnology (14).

In agricultural production, processing, storage, and transportation, nanotechnology mitigates chemical spread, enhances herbicide and pesticide efficacy, and boosts yields while safeguarding soil and water resources. Specific applications like nano-herbicides, nanofertilizers, and nanopesticides are tailored to improve productivity and resilience against biotic and abiotic stressors without environmental contamination (10, 54, 55). The Green Revolution's historic gains in food production have come with ecological costs due to excessive chemical use, impacting ecosystems and human health. Nanotechnology offers a pathway to mitigate these impacts by refining agricultural inputs and deploying sensors for rapid environmental monitoring (52, 72). Emulating natural processes through nanotechnological interventions presents a promising avenue for sustainable agriculture (53, 40).

This paper aims to delve deeper into these concepts, exploring how nanotechnology can address current agricultural challenges and pave the way for future sustainability in global food production systems.

What is Nanotechnology?

Nanotechnology, derived from the Greek word "nanos", meaning 'dwarf' or 'small', primarily involves the manipulation

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DOI: https://doi.org/10.21276/AATCCReview.2025.13.01.353

of materials at the level of individual atoms, molecules, or ions through processes such as separation, solidification, and deformation. According to the US Environmental Protection Agency (2007), nanotechnology is the science of understanding and controlling matter at dimensions typically between 1 and 100 nanometers (nm), whose unique physical properties enable novel applications (58, 81). This interdisciplinary approach makes it possible to research and utilize physical and chemical properties at the molecular level. Applications range from medicine to agriculture (23).

The Visionary Trailblazers of Nanotechnology: In 1959, Richard Feynman, an American physicist and Nobel Prize winner, introduced the concept of nanotechnology. During the annual meeting of the American Physical Society at Caltech, Feynman gave a lecture entitled "There's Plenty of Room at the Bottom". This influential lecture was later published in 1961 as the final chapter of the book "Miniaturization". About 15 years after Feynman's groundbreaking lecture, the Japanese scientist "Norio Taniguchi" was the first to use the term "nanotechnology" to describe semiconductor processes in the nanometer range. Taniguchi emphasized that nanotechnology involves the manipulation of materials at the atomic or molecular level, including processes such as processing, separation, consolidation, and deformation. Following Taniguchi's work, American engineer K. Eric Drexler became known for his contributions to molecular nanotechnology, particularly the development of nanosystems and the fabrication of nanomachines. Heinrich Rohrer, a Swiss physicist, was awarded the Nobel Prize in Physics in 1986 together with Gerd Binnig for the invention of the scanning tunneling microscope (STM). In addition, Prof. C.N. Rao, an Indian drugstore, gained fame for the synthesis of carbon nanotubes with Y-junction and is considered one of the leading figures in Indian nanotechnology (8).

What are NPs?

A nanoparticle is typically defined as a particle, whether of natural or manufactured origin, that measures between 1 to 100 nms in at least one dimension (Figure 1). To put this scale into perspective, one nm is one billionth of a meter. Examples of NPs are nanoemulsions, carbon nanotubes, quantum dots, nanorods, and micro- and nanocapsules. It is important to note that NPs have physical properties that can differ significantly from those of their solid counterparts. Key characteristics of NPs include their morphology, hydrophobicity, solubility, release of toxic species, surface area, roughness, surface species contamination or adsorption history during synthesis, production of reactive oxygen species like O_2/H_2O, structural composition, competitive binding sites with receptors, and tendencies toward dispersion or aggregation (1).

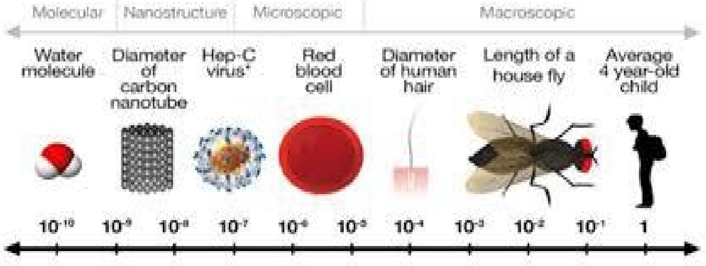


Fig. 1. Scale of NPs (35)

Green technology employed in the synthesis of Nps

NPs (NPs) can be synthesized from algae, plant extracts, and agricultural waste using green technologies. This approach offers a cost-effective, environmentally friendly, and manageable alternative to conventional physical and chemical methods (32, 63). These materials have potential applications in enhancing crop productivity and addressing agronomic challenges. Plant-based sources and agricultural waste present advantageous options for biogenic NPs, as protocols involving these sources are devoid of toxic substances. Various types of NPs can be synthesized using plant extracts such as Aloe vera, garlic, lamb's quarters, neem, sweet orange, bhringraj, Indian privet, mango, soybean, and algae. Moreover, agricultural waste materials such as bagasse, eggshells, rice husks, mango peels, corn cobs, and bamboo leaves, among others, can be utilized for nanoparticle synthesis (Tables 1 and 2).h was much higher width than the present findings while [17] recorded 0.5, 0.9, 1.5, 2.7 and 4.0 mm, respectively, was corroborated with the present findings.

Length and width of *E. materna*

The body length as well as width of larvae undergoing six instars, was greater than the larvae having five instars. The instarwise mean body length of the male larvae having five and six instars were 6.94, 12.16, 23.40, 43.70, 68.10 mm and 7.27, 10.32, 17.25, 25.75, 47.89, 74.86 mm, respectively (Table 2). Likewise, the females having five and six instars measured 7.08, 13.62, 22.65, 40.75, 70.85 mm, and 6.95, 11.0, 19.40, 26.6, 45.5, 72.0 mm, respectively. Regarding width, there was a considerable increase noticed in both the sexes during the fourth and fifth instar stage of larvae having five instars. In fourth instar the width of the male and female larvae measured 4.33 and 4.30 mm, respectively and in the fifth instar stage it was 8.55 and 9.3 mm, respectively. In the case of larvae having six instars, the was a noticeable increase in width found from fourth to sixth instar period. During that period the mean width measured in males and female was 3.08, 4.84, 9.62, and 2.95, 4.78, 9.56 mm, respectively (Table 2). In the present study, the mean total length and width of the grown up male larvae (final instar) which had five and six instars was 68.1, 74.9 mm and 8.55, 9.62 mm respectively while in female it was 70.9, 72.0 and 9.3, 9.56 mm respectively. [23] and [29] recorded much reduced length and width but the findings of [17] supports the present results. They measured the length and width of grown up larvae ranging 67.5–74.0 mm and 8.54 and 9.0 mm, respectively irrespective of sex and number of instars.

There was little difference was noticed both in the length and width of the pupa. When compared to pupa developed from larvae with five instars, the mean length of the pupae from larvae with six instars was more measuring 32.0 (male) and 32.70 mm (female), whereas in case of pupa developed from larva with five instars measured 30.96 mm and 31.25 mm, respectively. The mean width of the pupa measured 9.74 and 10.20 mm in case of male and female *E. materna* undergoing development in larvae with five instars and it was 10.04 and 9.40 mm, respectively incase of pupa developed from larva with

Table 1. NPs produced using various plant species

Plant	Type of NPs	References
Aloe vera	Gold, Silver, Copper, Zinc Oxide	38, 49
Garlic	Silver	68
Cashew	Gold/Silver bimetallic	75
Neem	Gold/Silver bimetallic	73
Bathua	Gold, Silver	20
Sweet Orange	Silver	39
Bhringraj	Silver	65
Chaste tree, Almond, Mango	Gold	44, 61, 86
Tomato	Zinc	77
Soybean	Palladium	60

Table 2. NPs derived from agricultural waste of wild-growing plants

Agro-waste	NPs	References
Tea waste	Iron	28
Tea leaf extract	Silver	47
Egg shell	Gold	16
Grape waste	Gold	43
Banana peel extract	Gold	7
Papaya fruit extract	Silver	33

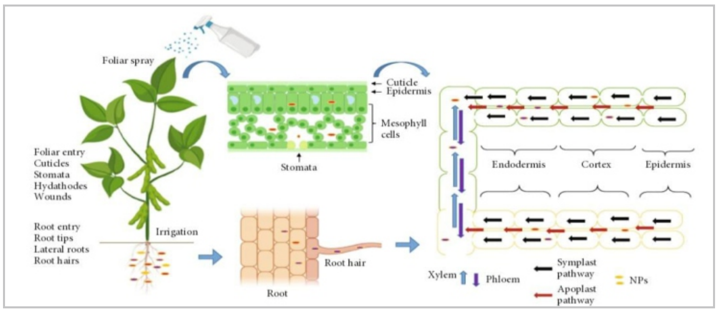
Uptake and Movement of NPs:

In the soil environment, NPs (NPs) undergo a series of biogeochemical transformations that affect their bioavailability and potential toxicity. After interaction with plant roots, NPs migrate to the aerial parts of the plant and accumulate in cellular or subcellular organelles. The initial adsorption of NPs by plant roots is the most important step in their bioaccumulation (57).

The size of the NPs plays a crucial role in their absorption. It allows penetration through the pores of the cell wall or the stomata of the plant and determines the subsequent transport processes into the cells or organelles within the plant cells, thereby influencing their accumulation, toxicity and transport kinetics (79). In addition, the shape of the NP correlates with the surface area, the tendency to agglomerate and the reactivity on cell surfaces or in plant structures (83).

Nanoparticles (NPs) applied to leaves can penetrate through stomata or cuticles. The cuticle serves as a primary barrier on leaves, limiting the penetration of NPs smaller than 5 nm. NPs larger than 10 nm enter the cell through the stomata and are transported into the plant vasculature via apoplastic and symplastic pathways (70). The transfer of NPs with a size of 10 to 50 nm typically occurs through the cytoplasm of neighboring cells (symplastic pathway), while larger NPs (50 to 200 nm) are translocated between cells (apoplastic pathway). Once internalized, the NPs move through the phloem sieve tubes along with the sugar flux, allowing bidirectional movement and accumulation in roots, stems, fruits, grains, and young leaves, which act as major sap sinks (67).

The apoplastic pathway is known to be non-selective and is the path of least resistance favored by many water-soluble nutrients and non-essential metal complexes for translocation (6). The effective adsorption of NPs after foliar application is influenced by the application methods, the size of the NPs, the concentration, and the environmental conditions (83). Leaf morphology, chemical composition, the presence of trichomes, leaf exudates, and waxes are key factors influencing NP retention on the leaf surface (45) (see Figure 2).



Distinctive characteristics of NPs:

NPs exhibit unique characteristics distinct from larger materials due to their size, typically less than 100 nms. This size-specificity offers numerous advantages in nanotechnology (2, 85):

- Nanoparticles (NPs) exhibit heightened charge density and reactivity due to their small size.
- The large surface area relative to volume enhances surface atom activity compared to interior atoms.
- NPs' high surface-to-volume ratio grants them superior strength, heat resistance, lower melting points, and unique magnetic properties.
- Varied surface exposures among NPs influence atomic distribution, impacting electron transfer kinetics with adsorbed species.
- Tetrahedral NPs demonstrate the highest catalytic activity, followed by cubic and spherical structures, characterized by enhanced reactivity at sharp edges and corners.

Nanomaterials bring about a variety of beneficial effects in agriculture:

In the realm of nanotechnology, materials smaller than 100 nms behave markedly differently. The nanomaterials used and, postive and negative effects of NPs are shown in Table 3 and 4. Effect of nanoparticles on plant growth and their mechanism in stress condition (see figure 3, 4).

Nanotechnologies present several advantages due to the distinctive functional properties of NPs

- Improved solubility of NPs in suspension.
- Improved bioavailability of the molecules for the seed radicals.
- Improved targeted activity.
- Reduced environmental impact through safe and efficient transportation.
- Nano-fertilizers for balanced plant nutrition.
- Development and application of nano-pesticides.
- Utilization of nano-sensors in agriculture.
- Advancements in post-harvest technology.
- Utilization of bio-synthesized NPs in agricultural processes.
- Application of biosensors in aquaculture.
- Exploration of nano-biotechnology for analyzing gene expression and regulation.
- Monitoring the identity and quality of agricultural products.
- Advances in seed technology.
- Innovations in water management in agriculture.
- Application of plant growth regulators.
- Consideration of agricultural engineering aspects.
- Applications of nanotechnology in food technology.

Fig. 2. Illustrating nanoparticle uptake via various pathways and their transport routes within different parts of plants (3)

Table 3. Nanomaterials used and its effect on plant growth

Nanomaterials	Effects on plants	Crops	References
CuO	Greater amount of Organic matter	Wheat	18
SiO_2	Higher shoot biomass and increased grain mass	Rice	46
SWCNT	Enhanced the length of the roots	Onion & Cucumber	12
MWCNT	Absorb nutrients such as Zn, Mn, K, Ca, and Fe	Tomato	78
TiO_2	Promoted growth and heightened activity of glutamate dehydrogenase and glutamic pyruvic transaminase	Spinach	69
TiO_2	Reduction in hydraulic conductivity	Maize	26
TiO_2	Boosts chlorophyll levels	Wheat	48
Activated Carbon- based TiO_2	Enhanced seed germination	Tomato	76
ZnO	Enhanced biomass production	Mung bean	17

Table 4: The impacts of diverse NPs on various plant species

NPs	Plant species	Effects	References
Silver	Rye-grass, Maize Sorghum Rye-grass Brahmi Mung bean Wheat	**Positive** Stimulate plant growth **Negative** Root and shoot lengths increases at low concentrations but decrease at high concentrations. Decreased biomass, root length, and root growth Broken root cap and epidermis Seed germination was impacted by varying concentrations. Reduce shoot bulk and boost biomass. decline in growth	82 42 82 22 34
Zinc	Cucumber Chickpea Cluster bean Mung bean Groundnut	**Positive** Boost the amount of micronutrients Weight increase for dry shoots Boost biomass and lengthen the roots and shoots Boost germination and the development of roots and shoots At low concentrations, increase seed germination; at high concentrations, reduce	15 25 88 62
Zinc oxide	Cucumber Wheat Rapeseed	**Negative** Impeded the development of roots. Inhibition of the production of chlorophyll, which lowers photosynthetic efficiency. Decreased germination and concurrent inhibition of root development.	15 27
Silicon dioxide	Tomato Soybean	**Positive** Boost tomato seed germination at low concentrations. Impact of a promoter on germination.	29 89
Silicon	Basil	**Positive** Increase the leaf's fresh and dry weight.	37
Titanium dioxide	Mung bean, Ear-cress, Fennel, Wheat, Duckweed	**Positive** Improve plant growth, germination, and chlorophyll content	71
Aluminium oxide	Wheat Tobacco	**Positive** Markedly enhanced elongation **Negative** Reduce the growth and development of plants	24
Copper Iron	Wheat	**Positive** An increase in the proportion of germination Shortening of the root	31
Ferrous oxide	Ear-cress	**Negative** Impact of inhibition on development	22
CNTs	Barley, Soybean, Maize	**Positive** Boost the germination of seeds	46
MWCNTs	Tomato, Tobacco	**Positive** Boost plant height, growth, and bloom count	50

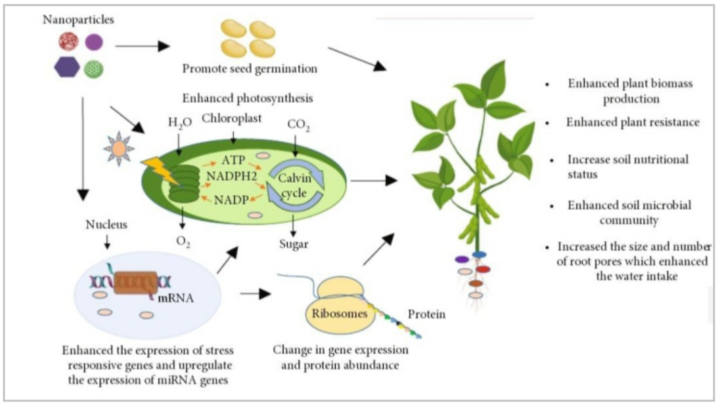


Figure 3: Effect of NPs on plant growth (1)

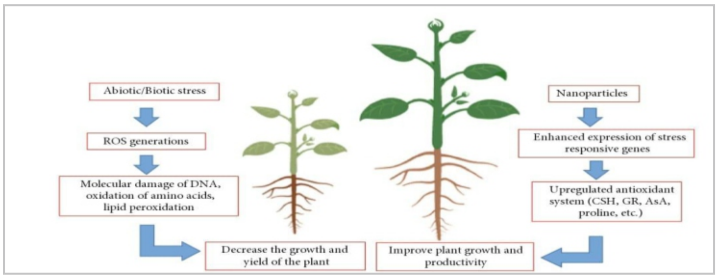


Figure 4: Mechanisms of NPs under stress condition (1)

Drawbacks of Nanotechnology

The term "Nanotechnology" has garnered attention due to its potential risks to health and the environment. These concerns are particularly relevant in specific contexts. Initial studies on nanomaterials have highlighted significant health hazards and toxicity issues, demonstrating potential harm upon entry into the human body, including tissue damage to vital organs. Another emerging application involves silver NPs used for delivering fertilizers to plants, leveraging their antimicrobial properties. However, research indicates that this approach may threaten ecosystems by damaging membranes, reducing grass growth rates, and impeding algal photosynthesis. Recovering silver NPs proves challenging, with certain plant species prone to maximal uptake and accumulation beyond safe limits in their tissues. Additionally, soybean, a major cash crop in many regions, has been cultivated using nanomaterials produced with fossil fuel equipment, which can deposit NPs locally on crops. Studies also reveal that conventional wastewater treatment methods impact plant-microbe interactions, potentially affecting nitrogen-fixing symbiosis sensitive to certain metals (14).

Utilization of nanomaterials in agriculture

Nanomaterials often have unique chemical, physical, or biological properties that differ from those of their larger counterparts, which can lead to other safety considerations. The agri-food industry has increasingly focused on nanotechnology as it offers significant potential to improve product quality. The rapid advances in nanotechnology since the late 20th century have enabled precise control over the production of nanomaterials with specific morphology and size. This progress has also introduced new concepts and methods that provide a solid foundation for solving unsolved problems in nutrient uptake and weed and pest control. Applications of nanotechnology in agriculture include the targeted delivery of various agrochemicals, research into the mechanisms of plant diseases, and advances in genome enhancement (1).

Nanotechnology for controlling weeds

Herbicides are known to damage entire ecosystems and food webs. Despite efforts to reduce herbicide use through the development of controlled-release and targeted-delivery herbicides that are safe for users and the environment, these technologies have not yet been widely adopted. Herbicide resistance is also a serious problem, as plant communities are constantly exposed to an herbicide that may be slightly susceptible to one herbicide in one season and another herbicide in another season (9).

In this challenging scenario, nanotechnology offers promising opportunities for the development of nanoherbicides with highly specific, controlled release mechanisms that increase efficiency and reduce weed competition in various crop production ecosystems. Nanoscale particles and materials have significantly different properties and effects compared to larger particles of the same chemical composition. The precise control of nanostructures, such as nanocapsules, enables the development of slow-release herbicides that provide environmentally friendly seasonal weed control without leaving toxic residues in the soil or environment (59). By integrating a "smart delivery system" with active ingredients, nano-herbicides can achieve effective weed control with less than traditional herbicide rates. In addition, nano-sized herbicides can bind with soil particles and inhibit the growth of weed species that have developed resistance to conventional herbicides.

Advanced delivery mechanism

Research is focused on the development of herbicide molecules that target specific receptors in the roots of weeds and are encapsulated in NPs. These molecules are designed to penetrate the weed's system and translocate to parts of the root system that inhibit glycolysis of food reserves, ultimately leading to starvation and death of the targeted weed plants (13) (Figure 5).

In rainy areas, the application of herbicides can lead to vapor loss if there is insufficient soil moisture. As accurate prediction of rainfall remains a challenge, it is difficult to apply herbicides in anticipation of rainfall. The controlled release of encapsulated herbicides is expected to be effective in controlling competition from weeds adjacent to crops.

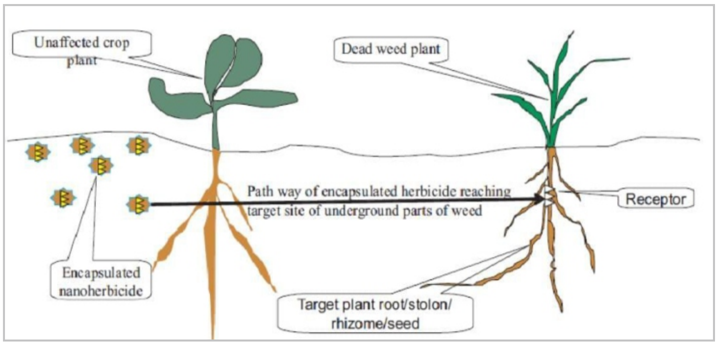


Figure 5: Efficient deployment of nanotechnology encapsulated herbicides in agricultural weed management (35)

Nanotechnology for managing pests

Minimizing the use of pesticides through targeted application to pests is critical to reducing costs and losses in crop production as well as reducing environmental impacts (74). This goal can be achieved by extending the release time and improving contact through a high surface area to volume ratio (4, 41).

Nanoparticle-based pesticide formulations

Research in nanotechnology has led to the development of various nanoformulations for crop protection, including nano-insecticides, nano-pesticides, nano-fungicides, and nano-nematicides. Nano-pesticides are tailored to improve solubility, enable slow release of active ingredients, and prevent degradation. To achieve these goals, the chemical nature and carrier molecules need to be modified, which are categorized into organic polymer-based formulations, lipid-based formulations, nano-sized metals and metal oxides, and clay-based nanomaterials, among others. There are some leading nanoformulations for agricultural applications (30).

1. **Nano-emulsions.**
2. **Nano-suspensions.**
3. **Polymer-based NPs.**
4. **Nano-encapsulation.**
5. **Nanospheres.**
6. **Nanogels.**
7. **Nanofibers.**

The primary benefits of employing nano-pesticides instead of traditional pesticides include (80):

- Nanotechnology enables the development of highly specific and environmentally friendly pesticide formulations.
- Nano-pesticides offer benefits like targeted delivery and controlled release, optimizing pesticide use, and reducing residues and pollution.
- Enhanced droplet adhesion and improved dispersion on plant surfaces increase bioactivity compared to conventional pesticides.
- Nano-pesticides contribute to sustainable agriculture by reducing chemical use, minimizing toxic residues, and enhancing crop protection outcomes.

Limitations of nano-pesticides usage (87)

Nano-particles, specifically nano-pesticides, present uncertainties regarding their impacts on human and environmental health.

These substances have the potential to create new types of soil and water pollution due to their perceived extended durability and increased toxicity in comparison to traditional pesticides.

Nanotechnology for managing nutrients

In agricultural crop production, nanotechnology plays a crucial role in reducing nutrient losses associated with conventional fertilizer applications on farms. Urban agriculture, supported by nanotechnology, has significantly contributed to enhancing food security and improving nutrition (66). Despite concerns about the potentially toxic effects of nanoparticles (NPs) on plants, soil, and water bodies, the main goal of integrating NPs in agriculture is to reduce dependence on hazardous materials such as pesticides and fertilizers (84).

Traditional chemical fertilizers have long been used to increase crop yields, but their excessive application has resulted in environmental challenges such as nutrient imbalances and soil degradation, leading to reduced soil fertility and nitrate leaching that contaminates groundwater and impacts ecosystems. Currently, there is a pressing need to develop smart materials capable of releasing nutrients slowly and consistently to targeted areas, thus promoting environmental sustainability. Various types of NPs have been developed for this purpose, either serving as plant nutrients themselves or acting as carriers for nutrient delivery (19).

For example, graphene has emerged as a promising material for delivering plant nutrients because it can release nutrients in a controlled manner, thereby improving nutrient efficiency and supporting sustainable agricultural practices (21).

Nanotechnologies in agricultural chemicals can involve modifying the chemicals themselves or combining them with other components. For instance, nutrients can be enclosed within nanoporous materials or delivered as particles or emulsions at the nano-scale level (36). These applications aim to achieve targeted delivery and sustainable release of nano-agrochemical products in response to environmental signals and biological needs. This approach enhances nutrient efficiency, reduces soil toxicity, mitigates the potential adverse effects of excessive use, and lowers costs associated with frequent treatments (64).

Organic nanoparticles such as chitosan, liposomes, and dendrimers are utilized for nano-encapsulation to improve stability, delivery, and availability of nutrients (e.g., vitamins, and minerals) and agrochemicals (56). Inorganic nanoparticles like ZnO, SiO_2, and TiO_2 are also widely used in these advanced delivery systems (5).

Future Scope

The future of nanotechnology in agriculture is vast and encompasses various promising advancements:

1. Smart Nano-fertilizers and Nano-pesticides: Development of highly efficient, biodegradable, and slow-release fertilizers and pesticides to enhance crop yield with minimal environmental impact.

2. Precision Agriculture: Integration of nanosensors and smart delivery systems for real-time monitoring of soil health, moisture levels, and plant nutrient uptake.

3. Genetic Engineering and Biotechnology: Use of nano-biotechnology to improve plant traits, enhance stress resistance, and develop genetically modified crops with superior yield and quality.

4. Nano-materials in Post-Harvest Management: Development of nano-coatings, smart packaging, and antimicrobial agents to extend shelf life and reduce food waste.

5. Water Purification and Management: Employing nanotechnology for efficient water filtration, desalination, and sustainable irrigation solutions to address water scarcity.

6. Carbon Sequestration and Soil Remediation: Utilizing nanoparticles for soil health improvement, pollutant degradation, and carbon capture to mitigate climate change effects.

7. Nano-enabled Disease Detection and Control: Development of rapid and precise diagnostic tools for detecting plant diseases and pathogens at an early stage.

Challenges

Despite its significant advantages, the adoption of nanotechnology in agriculture faces several challenges:

1. Environmental and Health Risks: The long-term impact of nanomaterials on soil microbiota, plant health, and human safety remains uncertain.

2. Regulatory and Ethical Concerns: The lack of standardized regulations and ethical considerations surrounding nanotechnology applications in food production raises concerns.

3. High Production Costs: The synthesis and application of nanomaterials require advanced technologies, making them costly and limiting accessibility for small-scale farmers.

4. Potential Toxicity and Bioaccumulation: Unintended consequences such as bioaccumulation of nanoparticles in plants, animals, and human systems pose risks that require extensive research.

5. Limited Awareness and Adoption: Farmers and stakeholders may be hesitant to adopt nanotechnology due to a lack of awareness, education, and reliable field trials.

6. Scalability and Commercialization: Transitioning nanotechnology from research to large-scale commercial applications requires substantial investments, infrastructure, and market acceptance.

Conclusion

Nanotechnology represents a transformative innovation in agriculture, offering solutions to critical challenges like crop productivity, environmental sustainability, and resource scarcity. By enabling precise delivery of agrochemicals and nutrients, nanotechnology enhances efficiency while minimizing ecological harm. Applications like nanoherbicides and nanopesticides improve yield and resilience against stresses, addressing the limitations of conventional methods. Its potential spans smart packaging, nanosensors, and nutrient management, fostering sustainable practices. However, concerns over toxicity and environmental impact require further research. Overall, nanotechnology promises a sustainable path forward, revolutionizing the food production system while mitigating the ecological costs of traditional agricultural practices.

Acknowledgement

We gratefully acknowledge the opportunity to publish this review paper in the esteemed "Agriculture Association of Textile Chemical and Critical Reviews Journal". We acknowledge Dr. Vijay Bharti and Dr. Anuradha Shah, Professors, Division of Agronomy, Sher-e-Kashmir University of Science and Technology of Jammu for their valuable support and also express gratitude to all collaborators whose discussions and contributions enriched the content of this paper**.**

Conflict of interest: Authors do not have any conflict of interests to declare.

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